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Carrier-rebalanced interband cascade lasers require very low input powers

Chul Soo Kim, Mijin Kim, Chadwick Canedy, William Bewley, Charles Merritt, Igor Vurgaftman, Joshua Abell, and Jerry Meyer

Design innovations have dramatically improved the threshold input power and all other performance characteristics of interband cascade lasers operating in the midwave-IR.

The recent availability of midwave-IR (i.e., 3–6μm) semiconductor lasers capable of emitting narrow spectral lines at ambient or thermoelectric-cooler temperatures (above −20°C) has spawned the development of a new generation of chemical sensing systems designed to exploit the prevalence of strong mid-IR spectroscopic signatures. Widespread use of these sensors is expected in such applications as greenhouse gas monitoring, control of combustion and other industrial processes, sensing of chemical and biological agents, and leak detection. Although the required laser output powers tend to be rather modest ($\leq$1mW), minimizing the drive power can be critical because the most attractive systems will be quite compact and often powered by batteries.

Several distinct classes of mid-IR semiconductor lasers are currently being developed. For example, recent advances have substantially extended the spectral range of conventional antimonide-based quantum-well (QW) diodes, although to date room-temperature (RT) continuous-wave (CW) operation has been achieved only up to wavelengths slightly beyond 3μm.[1] The most widely publicized approach has been the indium phosphide-based quantum cascade laser (QCL), which employs multiple stages of QWs stacked in series. This configuration splits the usual bands of available quantum states for electrons into subbands. Each electron injected into the device can emit a cascade of photons by making an intersubband transition (emitting one photon) in each stage that it traverses. Although multi-watt RT CW output powers have been generated, QCL threshold current densities (the level at which lasing begins) tend to be high,[2,3] $\approx$1kA/cm^2. Thus far, high performance with high yield is limited by material constraints to wavelengths beyond about 4μm.[4] A third alternative is the antimonide interband cascade laser (ICL),[5,6] which combines the interband active transitions of a conventional diode laser with the multiple cascaded stages of a QCL. Previous ICLs demonstrated spectral coverage of at least 2.9–4.2μm, and CW operation up to 72°C.

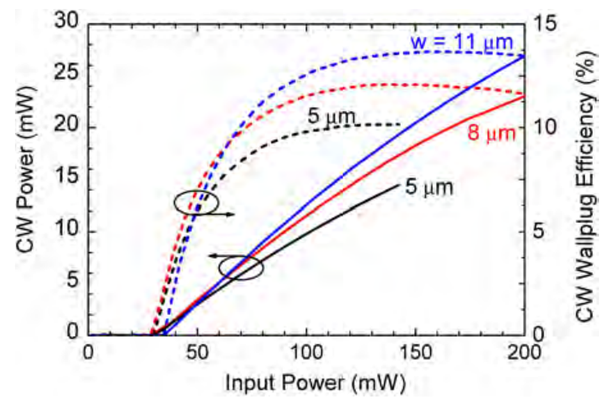

Figure 1. *Continuous wave (CW) output power (left scale) and wallplug efficiency (right scale) as functions of input power at 25°C for narrow-ridge interband cascade lasers (ICLs) emitting at a wavelength of about 3.7μm. The laser cavities had high-reflectance coatings on one facet and were 0.5mm long. Data are shown for three different ridge widths (w), varying from 5 to 11μm.*

A distinctive feature of the ICL is that whereas light is generated via radiative recombination of electrons and holes (as in a conventional diode laser), no holes are actually injected into the device. They are instead created internally at carefully designed semimetallic InAs/GaSb (indium arsenide/gallium antimonide) interfaces when an external electric field is applied. Our recent detailed simulations[7] of the carrier statistics showed

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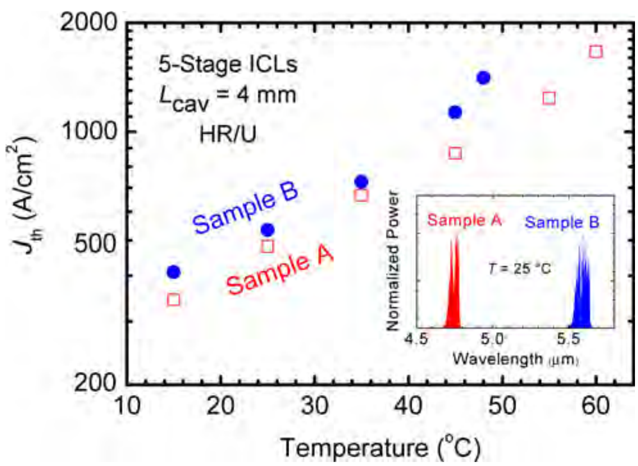

Figure 2. *Temperature dependence of CW threshold current densities (J_{th}) of narrow-ridge ICLs with five cascade stages. The ridges each had one high-reflectance and one uncoated facet (HR/U) and were 4mm long (L_{cav}) by 10.9μm wide (sample A) and 10.3μm wide (sample B), respectively. The inset shows CW emission spectra at 25°C.*

that although this process produces equal densities of electrons and holes, most of the generated electrons remain in the electron injector whereas most of the holes transfer efficiently to the active region via a relatively thin hole injector. Consequently, the hole population in the active QWs has substantially outnumbered the electrons in all previous ICL designs. Because that condition exacerbated the already-deleterious effects of free carrier absorption of light (i.e., internal loss) and Auger non-radiative recombination (which removes carriers), the resulting efficiency and optical gain per unit of injected current density remained far below the structure's ideal capacity.

However, the calculations further suggested that very heavy n-doping of the electron injectors, to the mid-10^{18}cm^{-3} range, should eliminate the carrier imbalance. Although most of the additional electrons continue to populate the injector, a fraction transfer to the active QWs to roughly equalize the electron and hole populations there. This 'carrier rebalancing' maximizes the optical gain per unit current density and also reduces the internal loss because far fewer holes are required to generate the threshold gain.

Redesigned ICLs incorporating carrier rebalancing have, by several key figures of merit, displayed record-setting performance compared to all previous mid-IR semiconductor lasers. For pulsed emission at about 3.7μm, we observed a RT threshold current density as low as 167A/cm^2, at a threshold voltage of 2.1V. The corresponding threshold power density of 0.35kW/cm^2 is far below all previous ICL results. Performance varies depending on the dimensions of the 'ridge,' which is etched into the structure to laterally confine the lasing mode. A narrow ridge displayed CW lasing up to 109°C, and other ridges emitted more than 150mW CW at RT. Figure 1 illustrates the CW output power and wall-plug efficiency (optical output power divided by electrical input power) as functions of input power at 25°C for three 0.5mm-long laser cavities with high-reflection coatings on the back facet. The maximum wall-plug efficiency of 13.5% is only slightly lower than that of the best QCLs emitting at longer wavelengths. The most remarkable finding is that none of the devices in Figure 1 requires more than about 35mW of input power to achieve CW lasing. The lowest RT CW input power reported to date for a QCL is 830mW, for a device with a partially transmitting high-reflectance output facet.[8] More typical QCL values, in the 2–5W range, are two orders of magnitude larger than the new ICL result.

Figure 2 shows that such performance can be extended to considerably longer wavelengths as well (about 4.8 and 5.6μm for samples A and B, respectively).[9] Even in this spectral range, the RT CW threshold power densities of <1kW/cm^2 are more than an order of magnitude lower than the best values (≈12kW/cm^2) ever reported for state-of-the-art QCLs. The maximum operating temperatures were 60°C (for sample A) and 48°C (for sample B).

Rebalancing of the hole/electron population ratio in interband cascade lasers has substantially reduced the devices' threshold input powers, to values more than an order of magnitude below state-of-the-art QCLs emitting in the same spectral range. Because most chemical spectroscopy systems do not require high output power, operation near threshold will substantially extend the battery lifetimes and reduce system complexity. We have also demonstrated single-mode ICLs,[10] and are working to improve those. Other research will focus on further reducing the current and power thresholds of ICLs and concomitantly increasing their output power and wallplug efficiency. These characteristics should position the new generation of carrier-rebalanced ICLs as the mid-IR lasers of choice for applications requiring compactness, low cost, and low power budgets.

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